DEPARTMENT OF THE AIR FORCE
AIR FORCE CIVIL ENGINEER CENTER

21 July 2015

AFCEC/CIBW
706 Hangar Road
Rome, NY 13441-4105

Mr. Patrick Shinabery
Arizona Department of Environmental Quality
1110 West Washington Street, 4415B-1
Phoenix, Arizona 85007

Subject: Response to Williams AFB ST012 Technical Support
Review of Weekly Progress Report 18-May-2015
Energy Balance for ST012 Soil Volumes through
May 18, 2015, from Lloyd "Bo" Stewart, PhD, PE
Praxis Environmental Technologies, Inc., Dated May 29, 2015
Former Williams Air Force Base

Dear Mr. Shinabery:

The Air Force is pleased to submit the below responses to Arizona Department of Environmental Quality (ADEQ) for the Praxis Environmental Technologies, Inc., energy balance calculations and discussion dated 29 May 2015 for the Site ST012 Steam Enhanced Extraction located at the former Williams Air Force Base in Mesa, Arizona.

A primary purpose for performing an energy balance during steam injection, and assessing the related hydraulic containment, is to determine the potential for NAPL to be transported away from the thermal treatment zone.

Response:
While an energy balance can be used for this purpose, the primary purpose of the energy balance is to track at a high level against the design model. The design and operating plan did not include using the energy balance for assessment of hydraulic control.

Heated NAPL moving under pressures associated with steam injection will move with the steam and/or hot water. Hence, if water flow is outward, then NAPL flow is outward and this flow is enhanced if heated. The transport of energy outside the target treatment zones is an indicator of such NAPL migration. Adversely displaced NAPL increases the burden on later treatment by other means to meet the remedial action objectives.

Response:

Noted. Monitoring of hydraulic containment does not indicate outward water flow. There is some perimeter heating occurring as expected by the design model but no indication of energy transport to the perimeter monitoring wells. The localized occurrence of LNAPL at external perimeter wells is not interpreted as adverse NAPL displacement but is related to hydraulic effects on LNAPL that was already present outside the thermal treatment zones.

The energy requirement for heating the soil at ST012 is presented in Table 5.5 of Appendix D in the SEE Work Plan. The energy value reported in Table 5.5 is 786,533,000 BTU/F based on a soil volume of 615,149 cubic yards (cy). This volume is the thermal treatment zone (TTZ) multiplied by a factor of 1.5 (referred to as the Heated Zone, HZ), i.e., the volume of the heated zone is 50% larger than the TTZ. The required energy for heating the HZ soil volume to a specified temperature above ambient is presumably calculated by multiplying the provided energy value by the change in soil temperature.

$$Esoil = (786{,}533{,}000\ BTU/F)(T - Tamb)$$

Response:

Noted.

The weekly progress report through May 18, 2015 presents in Figure 20 a net energy in the soils (energy injected – energy extracted) of around 32,000,000 kWh (~109,194 MBTU). The energy injected as steam is shown as about 43,000,000 kWh and the extracted energy totals about 11,000,000 kWh.

Response:

An energy balance calculation is based on numerous assumptions and measurements which have various levels of uncertainty. Also, there are energy losses which are difficult to measure and/or estimate precisely, which if not accounted for result in an overestimation of the actual amount of energy in the steam zone. For example, the ST012 energy balance does not account for energy lost in the steam pipes, in the upper 140 ft of the injection wells (by conduction through the casing and grout to a vertical column surrounding each well), or by thermal conduction above and below the heated zone. Also, the injected steam quality is not 100% (i.e., some condensate exists in the generated steam resulting in lower overall energy content), so the energy balance likely over-represents the energy input. Therefore, the net energy delivered per a calculated energy balance is not representative of the amount of energy stored in the steam zones which is likely to be less when accounting for energy losses.

Using this soil energy value and an ambient temperature of 82 F (28 C) as indicated by the subsurface temperature monitoring, we find after rearranging the expression above,

$$T = T_{amb} + \frac{E_{soil}}{786{,}533{,}000 \frac{BTU}{F}} = 82\ F + \frac{109{,}194{,}000{,}000\ BTU}{786{,}533{,}000 \frac{BTU}{F}}$$

$$T = 221\ F = 105\ C$$

Response:

Noted, based on these inputs.

Based on the provided data, the average soil temperature throughout the HZ of all layers is expected to be 221 F (105 C) on May 18.

Response:

Noted, based on the inputs listed. However, this energy balance does not account for the additional heat losses and steam quality noted previously.

However, the average temperatures presented on May 18 in Figure 6 for all layers of the TTZ (smaller than the HZ) are approximately 192 F in the LSZ, 140 F in the UWBZ and 90 F in the CZ; all three averages are well below the predicted average of 221 F.

Response:

The temperatures in each TTZ (as presented on Figure 6 of the weekly report) is an average of the thermocouple sensors available in each zone. TMPs that have failed are not included in the averages on the figure but are removed during the period of failure. Because the failures appear to be associated with areas that were at higher temperatures prior to failure, the recent average temperature in each zone likely underestimates the true average temperature. It is also worth noting that the design of the TMP layout was intended to monitor steam front progression in select locations and was not designed with the intent to develop average temperatures in each zone for the purposes of performing the type of calculations indicated below.

This large discrepancy in temperatures indicates significant energy has been transported outside the HZ volume rather used to further heat the HZ soils.

Response:

ADEQ's calculations are using the lower average temperatures to predict a larger volume effect and more influence beyond the TTZ than is actually occurring. In reality, the discrepancy in temperatures is due primarily to a combination of not accounting for the additional losses and the underestimation of actual subsurface temperatures as noted above.

For application to individual zones (i.e., CZ, UWBZ and LSZ), the total heating value of the soil provided in Appendix D can be converted to a more conventional soil heat capacity by dividing 786,533,000 BTU/F by the soil volume considered,

$$u_{soil} = \frac{786{,}533{,}000\ BTU/F}{615{,}149\ \text{cy}}\left(\frac{1\ cy}{27\ ft^3}\right) = 47.4\ \frac{BTU}{F\ ft^3}$$

With this unit soil heat capacity, the energy stored within each zone can be calculated from its soil volume and average temperature. For example, in the LSZ,

$$E_{soil,LSZ} = u_{soil}V_{LSZ}(T_{LSZ} - T_{amb}) = \left(47.4 \frac{BTU}{F\,ft^3}\right)(385{,}469 \times 27\ ft^3)(192F - 82F)$$
$$= 54{,}208\ MBTU = 15{,}886{,}100\ kWh$$

The soil volume for the HZ (from Table 5.3 of Appendix D) and the calculated energy content for all three soil zones are provided in the table below.

Parameter	**LSZ**	**UWBZ**	**CZ**
Thermal Treatment Zone Soil Volume, cy	256,979	113,212	39,957
Heated Zone Soil Volume, cy	385,469	169,818	59,936
Average Temperature (18-May-15), F	192	140	90
Temperature Change from Ambient, F	110	58	8
Volumetric Heat Capacity (u_{soil}), BTU/F/ft3	47.4	47.4	47.4
Soil Energy Content (E_{soil}), MBTU	54,208	12,592	613
Soil Energy Content (E_{soil}), kWh	15,886,100	3,690,200	179,600
Total Soil Energy Content (E_{soil}), MBTU	67,413		
Total Soil Energy Content (E_{soil}), kWh	19,755,900		

Response:

As noted previously, the average temperature reported based on the available thermocouple data likely underestimates the average temperatures in each zone.

The weekly progress report through May 18, 2015 presents the net energy in the subsurface of around 32,000,000 kWh (~109,194 MBTU). This total energy exceeds the total soil energy content calculated above using average soil temperatures. Based on the reported net energy in the soil, the average zone temperatures, and assuming the larger volume of the HZ indicates that approximately 40% of the energy in the soil is located outside the hypothetical HZ. For the TTZ, the majority of the energy in the subsurface is outside the thermal treatment zone compared to inside; about 60% of the subsurface energy is beyond the TTZ boundaries. The transport of a large fraction of the energy away from the TTZ is inconsistent with the concept of hydraulic containment wherein water flow is toward the TTZ.

Response:

The calculations and conclusions drawn are very conservative and represent an overestimation of the actual energy in the subsurface as it does not account for the limitations of the temperature averages and additional heat losses. Additionally, the system design and operational strategy includes injecting steam in perimeter wells, knowing that a portion of the steam injected along the TTZ perimeter will flow outward. The selection of perimeter steam injection wells included locations with less or no evidence of NAPL presence. The process of perimeter steam injection is monitored to minimize NAPL movement at the site perimeter.

The amount of steam removed by the extraction wells, as represented in the energy balance, is skewed by the fact that steam must travel the full distance to the surface and through the vapor manifolds to the treatment system in order to be counted as steam. In reality, steam can enter the screened interval and be condensed by the counter-current flow of 8-11 gpm of motive water to the eductors. These wells act as 200 ft long condensers/heat exchangers. Steam is condensed and instead extracted as hot water. Therefore, the quantity of steam which has flowed to the extraction wells is difficult to calculate, but is larger than the ADEQ energy balance indicates (the energy is counted in the extracted water instead). The AF has a monitoring program to account for this mechanism by measurement of extracted groundwater temperatures at the well location. It can be assessed by calculation whether a well is likely to be flowing steam. These monitoring data are used as a basis to make informed decisions related to pressure cycling at selected site locations.

Additional Considerations for the Energy Balance and Hydraulic Containment

The soil thermal properties used to calculate this energy value of 786,533,000 BTU/F were not provided in Appendix D. However, the volumetric energy content of soil with water and steam vapor is a basic calculation provided by numerous references (e.g., Marx & Langenheim, 1959; Mandl & Volek, 1969; Menegus & Udell, 1985):

$$\begin{gathered} Soil\ Energy\ Content\ per\ Unit\ Volume\ (with\ steam\ vapor\ present) = \\ Energy\ in\ Solid\ Rock + Energy\ in\ Water\ + Energy\ in\ Steam\ Vapor = \\ e_{soil,steam} = \left[\rho_r c_{pr}(1-\varphi) + \rho_w c_{pw}\varphi S_s\right](T_s - T_{amb}) + \rho_v h_v \varphi(1 - S_s) \end{gathered}$$

In this expression, the parameter S represents the saturation of liquid water in the soil pore space, just as it does in the vadose zone. Pore space not occupied by liquid water is occupied by steam vapor. Notation and typical values for the other parameters in this expression are provided in the table below.

Parameters	**Ts** (266 °F)
Total Porosity (ϕ), nd	0.30
Solid/Rock Density (ρ_r), lb/ft3	165.5
Solid/Rock Heat Capacity (c_{pr}), BTU/lb/°F	0.24
Water Density (ρ_w), lb/ft3	58.34
Water Heat Capacity (c_{pw}), BTU/lb/°F	1.02
Steam Vapor Density (ρ_v), lb/ft3	0.094
Steam Vapor Enthalpy (h_v), BTU/lb	1,170

Substituting these parameters into the steam zone energy expression above yields the energy content in the soil per unit volume as a function of the pore space occupied by liquid,

$$e_{soil,steam}(BTU/ft^3) = [27.8 + (18.3)S_s](266 - 82) + 33(1 - S_s)$$

Substituting a value of one for the water saturation (no steam vapor) and dividing by the temperature difference yields the soil heat capacity when saturated with liquid water,

$$u_{soil}\left(\frac{BTU}{F\,ft^3}\right) = 27.8 + 18.3 = 46.1\ \frac{BTU}{F\,ft^3}$$

This calculated heat capacity of 46.1 is close to the value of 47.4 determined from the energy parameter in Appendix D, Table 5.5. The small difference is likely the result of slightly different parameter values (i.e., water and solid densities and heat capacities, steam zone temperature). The two soil heat capacity values are effectively equal with a water saturation of one indicating the SEE modeling presented in Appendix D did not consider the formation of a steam bubble in the subsurface and brings into question the consideration of steam bubble formation on hydraulic containment.

The formation of a steam bubble, commonly referred to as a steam zone, requires the inclusion of steam vapor in the calculation of the soil energy content. This is demonstrated in the expression above when S is less than one. Therefore, if a steam zone exists and is growing, the energy balance should account for it. Differing liquid/vapor contents in the soil pore space were input to the simple expression above for the soil energy content to illustrate the variation in soil energy. The results are provided in the table below,

Ss Liquid Saturation	**1-Ss** Steam Vapor Saturation	**usoil** (BTU/F/ft3)	**esoil,steam** (BTU/ft)
1.00	0.00	46.1	8,476
0.75	0.25	41.6	7,644
0.50	0.50	37.0	6,812
0.25	0.75	32.5	5,980

These calculations demonstrate that the energy content in soils containing a steam vapor are lower than the energy content in soil saturated with water at steam temperature. Therefore, where a steam bubble or steam zone is created, the energy required for heating is less than the energy predicted by the energy value provided in Appendix D. Assume for example that steam vapor occupies 50% of the pore space, the energy required to heat the soil volume is only 6,812 BTU/ft3 or 20% less than water-saturated soil value of 8,476. If steam vapor occupies pore space in the TTZ, as intended during steam injection, an even larger fraction than 40% of energy in the soil has been transported beyond the boundaries of the hypothetical HZ and contradicts the concept of a net inward flow of water.

The energy balance is inter-related to mass and volume balances (e.g., the existence of steam vapor versus liquid water in soil pore spaces) and hydraulic containment. Consider the mass of water in a unit volume of soil at steam temperature but without steam vapor,

$$m_{water,saturated} = \rho_w \varphi = \left(58.3\ \frac{lb}{ft^3}\right)(0.30) = 17.5\ \frac{lb}{ft^3}$$

Consider next the mass of water in a unit volume of soil that has 50% of its pore space occupied by steam vapor,

$$
\begin{aligned}
m_{water,steam} &= \rho_w \varphi S_s + \rho_v \varphi (1 - S_s) \\
&= \left(58.3\ \frac{lb}{ft^3}\right)(0.30)(0.50) + \left(0.094\ \frac{lb}{ft^3}\right)(0.30)(0.50) \\
&= 8.8\ \frac{lb}{ft^3}
\end{aligned}
$$

This simple mass balance demonstrates that a 1:1 ratio of mass injected versus mass extracted is not valid for describing hydraulic containment when a steam bubble exists.

Response:
The operation of the SEE system over the duration of the project has maintained an extraction to injection ratio greater than 2:1 (over 3.6:1 in the UWBZ). This ratio is higher during pressure cycling phases. Higher ratios result in a higher hydraulic gradient toward the site thereby further maintaining perimeter containment control.

A unit volume previously occupied by 17.5 pounds of water holds only 8.8 pounds of water if a modest steam bubble exists (S=0.5). The displaced 8.7 pounds of water must be accounted for in the extraction to maintain hydraulic control. This water displacement phenomenon is well described by EPA (Davis, 1998),

> *Initially, the steam that is injected will heat the well bore, and the formation around the injection zone of the well. The steam condenses as the latent heat of vaporization of water is transferred from the steam to the well bore and the porous media where it enters the formation. As more steam is injected, the hot water moves into the formation, pushing the water initially in the formation (which is at ambient temperature) further into the porous media. When the porous media at the point of steam injection has absorbed enough heat to reach the temperature of the injected steam, steam itself actually enters the media, pushing the cold water and the bank of condensed steam (hot water) in front of it.*

As implied in the EPA description and demonstrated by the simple water mass calculation, the ability to estimate the volume of the steam zone in the subsurface during steam injection is integral to the determination of hydraulic control.

Response:
As noted, this is an implied conclusion. The cited document does not identify this as a primary method for demonstrating hydraulic control. In fact, this method is not commonly used on steam remediation sites to demonstrate hydraulic control. The maintenance of the extraction to injection ratios cited above were established to ensure hydraulic control. Maintenance of overall hydraulic control has been established based on perimeter monitoring and reporting.

The volume of the steam zone is a major parameter in assessing an acceptable water mass balance. Put another way, one pound of uncondensed steam vapor displaces roughly

500 to 600 pounds of liquid water. Assessing hydraulic containment should include displacement of groundwater by steam vapor and ambient groundwater flow as well as condensed steam. Balances in the weekly progress reports consider only condensed steam and are inadequate for assessing hydraulic containment.

Response:
Water mass balances are one measurement evaluated; however, due to limitations of the data, additional reliable measures of hydraulic containment are perimeter water level measurements and hydraulic gradients. An expanding steam zone and displacement of groundwater results in a pressure gradient related to the larger volume occupied by steam than the equivalent liquid water it contains. This gradient is accounted for in the water level measurements collected at the site perimeter monitoring wells.

The operational data to determine whether enough energy has been injected to facilitate heating and steam break-through to the wells are the actual observed temperatures and flow rates at the extraction well, not a calculated quantity based on assumptions. Additional analysis of estimated formation water temperatures at each extraction well has been presented starting in the 15 June 2015 weekly report. It is prudent to use the field data to determine when pressure cycling and reduced steam injection rates are justified.

The Air Force agrees with the overall conclusion that at the time of the ADEQ comments, the energy delivered to the subsurface was in the range expected for achieving steam break-through to most of the extraction wells. However, site operational data did not support the empirical calculation and general conclusion(s) derived as a complete heat-up in all extraction wells has not occurred. Nonetheless, in areas where steam break-through has occurred pressure cycling has been initiated, such as in the northern part of the UWBZ from 8-22 June 2015, in the LSZ near LSZ5 beginning on 16 June 2015, and in the complete LSZ beginning on 22 June 2015.

References

Davis, E.L., Steam Injection for Soil and Aquifer Remediation, Ground Water Issue Paper, EPA/540/S-97/505, January 1998.

Mandl, G. and C.W. Volek, "Heat and Mass Transport in Steam-Drive Processes," SPEJ (March 1969), Transactions AIME Vol. 246, pp. 59-79.

Marx, J.W. and R. H. Langenheim, "Reservoir Heating by Hot Fluid Injection," Transactions AIME (1959) Vol. 216, pp. 312-315.

Menegus, D.K, and K.S. Udell, "A Study of Steam Injection Into Water Saturated Capillary Porous Media," Heat Transfer in Porous Media and Particulate Flows, ASME Heat Transfer Division, New York City (1985) Vol. 46.

Please contact me at (315) 356-0810, ext. 204 or catherine.jerrard@us.af.mil if you have any questions regarding this report.

Sincerely,

CATHERINE JERRARD
BRAC Environmental Coordinator

c: ADEQ - Patrick Shinabery
Administrative Record – Terie Glaspey
AFCEC – Catherine Jerrard
ASU Libraries – Dan Stanton
CNTS – Geoff Watkin
TechLaw – Michael Anderson
USEPA – Carolyn d'Almeida
USEPA – Eva Davis
UXOPro – Steve Willis
File